



$\gamma\gamma$ Physics Analyses at **BESIII**

September 24, 2015 | Christoph Florian Redmer
for the BESIII Collaboration

10th International Workshop on e+e- collisions from Phi to Psi

Motivation

$$a_{\mu} = \frac{g_{\mu} - 2}{2} = \frac{\alpha}{2\pi} + \dots = 0.001161\dots$$

$$a_{\mu}^{\text{theo}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{weak}} + a_{\mu}^{\text{hadr}}$$

Contribution	Result in 10^{-10} units		
QED(leptons)	11658471.885	± 0.004	Kinoshita et al. (2012)
Weak	15.4	± 0.2	Czarnecki et al. (2003)
HVP(leading order)	692.3	± 4.2	Davier et al. (2011)
HVP(higher order)	-9.84	± 0.07	Hagiwara et al. (2009)
HLBL	11.6	± 4.0	Jegerlehner, Nyffler (2009)
Total	11659181.3	± 5.8	
Experiment	11659208.9	± 6.3	

Prediction completely limited by hadronic contributions !

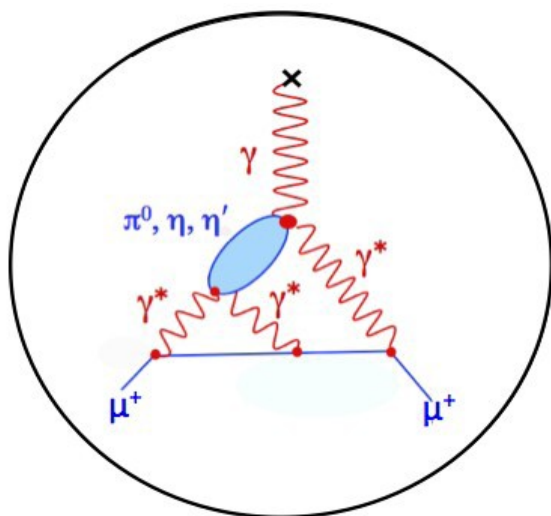
Challenge:

Perturbative methods cannot be applied in the relevant energy regime

Hadronic Light-by-Light

a_{μ}^{hLBL} not directly related to measurable quantities

- Interaction of virtual mesons with real/virtual photons



- Hadronic models
 - ChPT at lowest energies
 - pQCD at high energies
 - Intermediate region ?

Glasgow Consensus, arXiv:0901.0306
Jegerlehner/Nyffeler, Phys.Rept.477,1

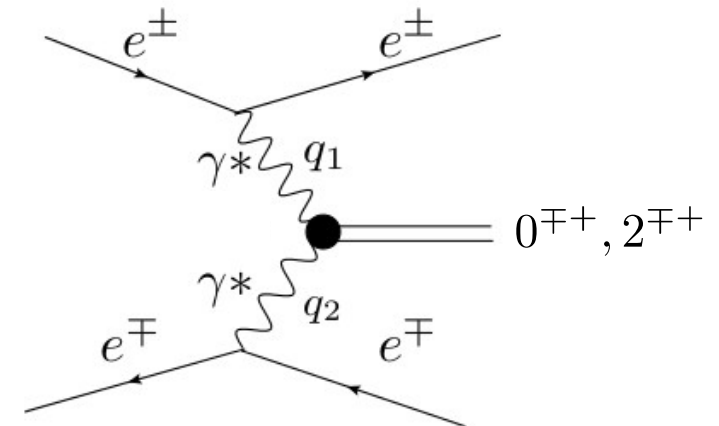
- Data driven approaches
 - Based on dispersion relations
 - Reduce model dependency
 - Reliable error estimates

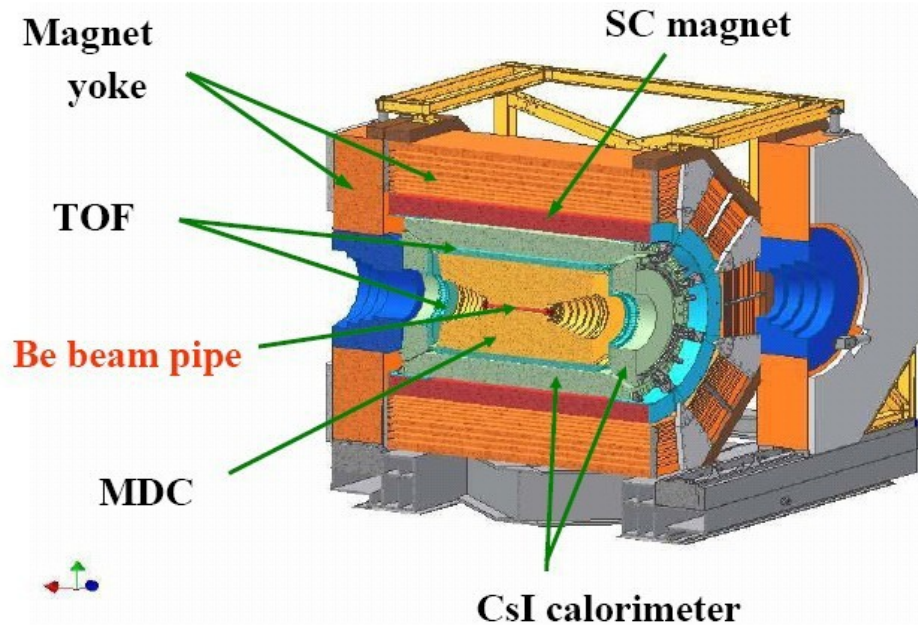
Collangelo, Hoferichter, et al. (Bern)
Vanderhaeghen, Pauk, et al. (Mainz)

- Transition form factors (TFF) as experimental input

Two-Photon Collisions

- Exchange of two photons in e^+e^- collisions
- Pseudoscalar, axial, and tensor states accessible
- $M_X \ll \sqrt{s}$
- $\sigma \propto \alpha^2 \ln^2 E$
- $\sigma \propto F^2(Q_1^2, Q_2^2)$, with $Q_i^2 = -q_i^2$
- Forward peaked kinematic
 - Experimentally challenging
 - Special tagging detectors recommended



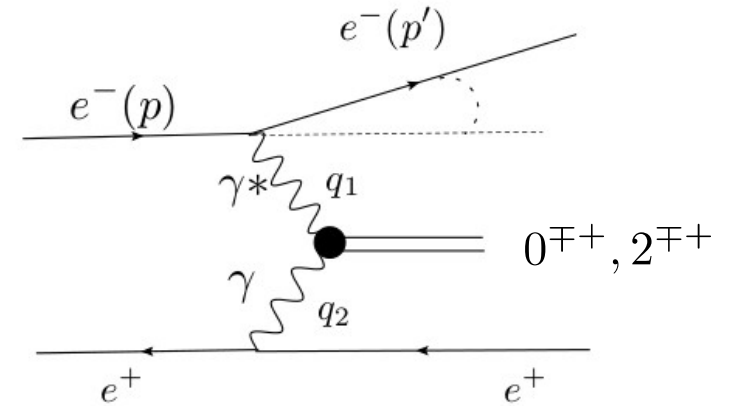


**World's largest data samples
of J/ψ , $\psi(2S)$, $\psi(3770)$, and
 $4 \text{ GeV} < \sqrt{s} < 4.6 \text{ GeV}$**

- Main Drift Chamber (MDC)
 - $\sigma(p)/p = 0.5\%$
 - $\sigma_{dE/dx} = 6.0\%$
- Time-of-flight system (TOF)
 - $\sigma(t) = 90\text{ps}$ (barrel)
 - $\sigma(t) = 110\text{ps}$ (endcap)
- EMC
 - 6240 CsI(Tl) crystals
 - $\sigma(E)/E = 2.5\%$
 - $\sigma_{z,\phi}(E) = 0.5 - 0.7 \text{ cm}$
- Muon Chambers
 - 8 – 9 layers of RPC
 - $p > 400 \text{ MeV}/c$
 - $\delta R\Phi = 1.4 \sim 1.7 \text{ cm}$
- Superconducting Magnet
 - 1 T magnetic field

Single-Tag Measurements

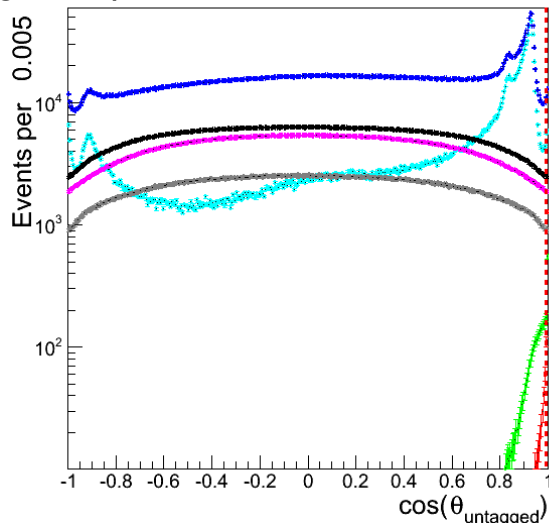
- Reconstruct
 - only one scattered lepton
 - Produced system
- Unmeasured lepton from momentum conservation
 - Require scattering angle to be small
 - Small virtuality
- $F(q_1^2, q_2^2) \rightarrow F(q_1^2, 0) \rightarrow F(q^2)$



Example: π^0, η

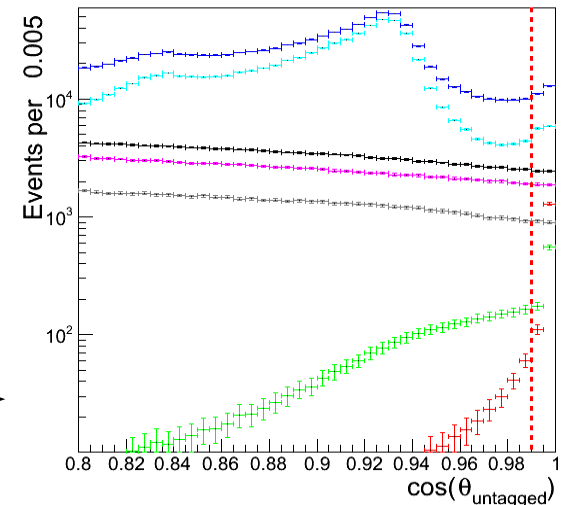
BESIII Monte Carlo, $\Psi(3770)$, $L_{int}: 927 \text{ pb}^{-1}$

Tagged Lepton: e^-



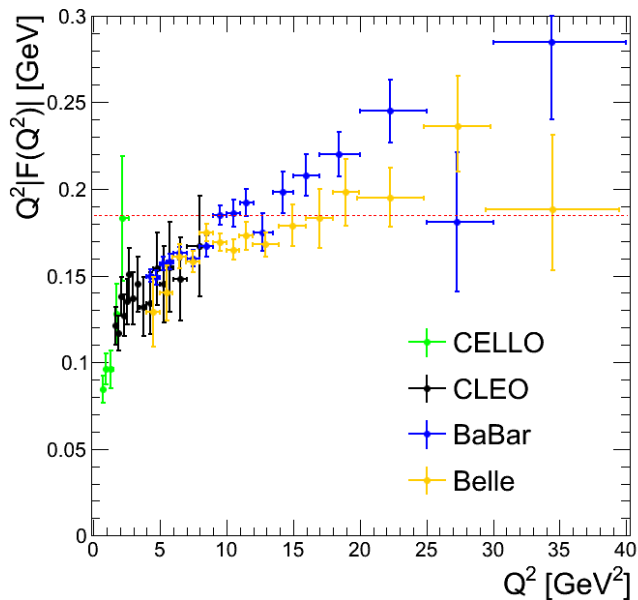
- π^0 2-Octet Model
- η 2-Octet Model
- $q\bar{q}$ continuum
- $\Psi(3770)$
- Rad. Return ($J/\Psi, \Psi'$)
- rad. Bhabha
- MC Sum

zoom

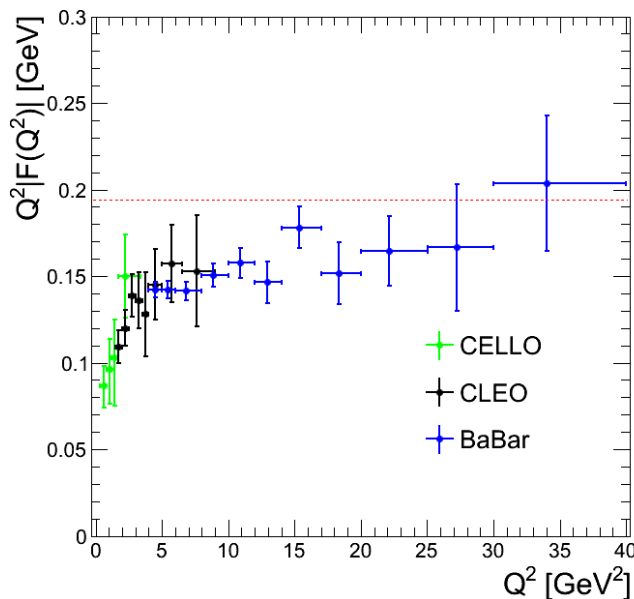


Existing Data

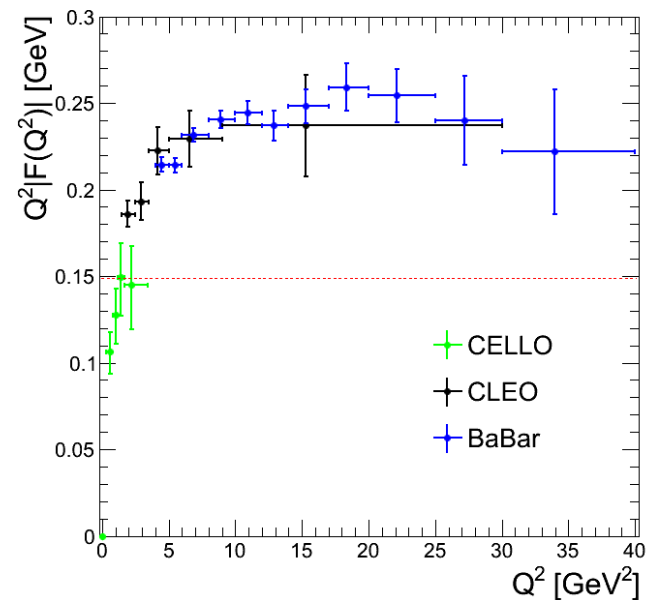
$$e^+e^- \rightarrow e^+e^- \pi^0$$



$$e^+e^- \rightarrow e^+e^- \eta$$



$$e^+e^- \rightarrow e^+e^- \eta'$$



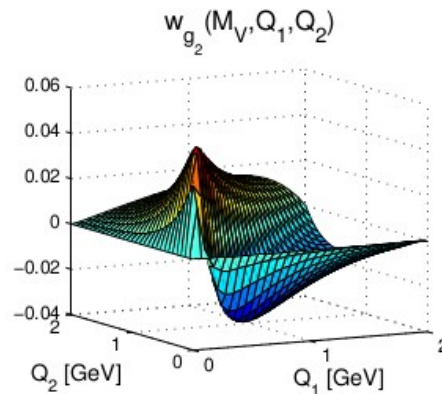
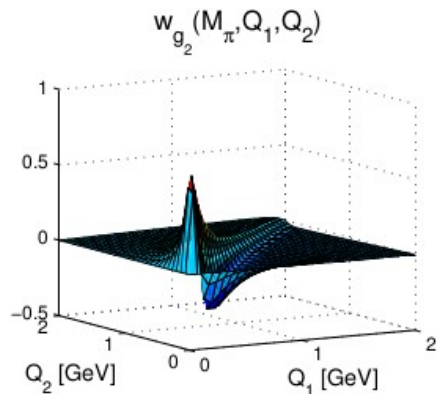
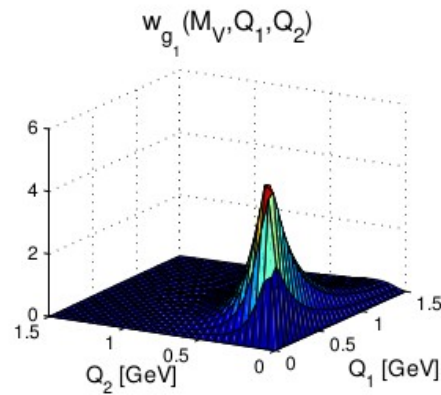
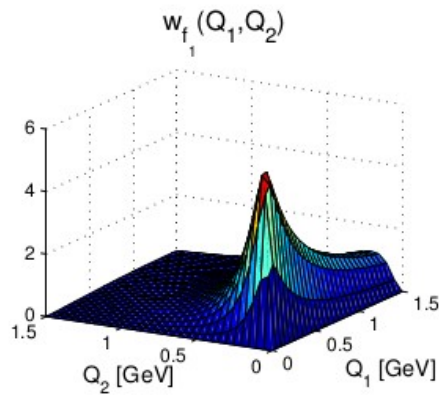
- Recent results from B-factories cover only large Q^2 ($5 < Q^2 \text{ [GeV}^2\text{]} < 40$)
- Discrepancy for π^0 between BaBar and Belle
- Data scarce at lowest Q^2
- Region of relevance for $(g-2)_\mu$

CELLO: Z.Phys.C49 (1991) 401
 CLEO: Phys.Rev.D57 (1998) 33
 BaBar: Phys.Rev.D80 (2009) 052002
 Phys.Rev.D84 (2011) 052001
 Belle: Phys.Rev.D86 (2012) 092007

Relevant Energy Range

2D integral representation for pion-pole contribution by Knecht, Nyffeler (2002):

$$a_{\mu}^{\text{HLbL};\pi^0} = \int_0^{\infty} dQ_1 \int_0^{\infty} dQ_2 \sum_i w_i(Q_1, Q_2) f_i(Q_1, Q_2)$$



- Universal weight functions w_i
- Form factor dependence f_i

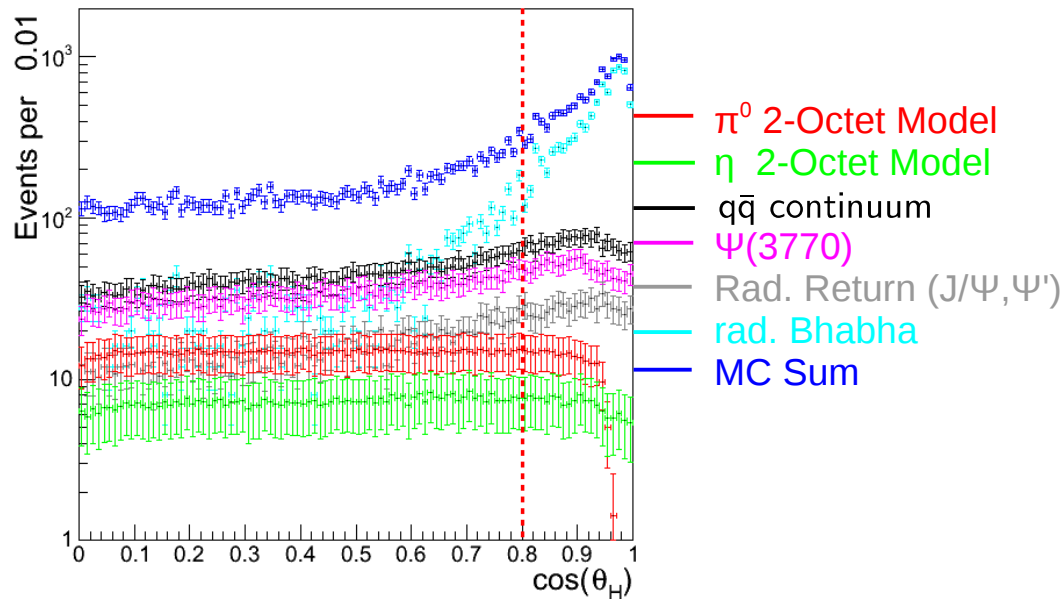
Relevant momentum regions:

0.25 – 1.25 GeV

Space-like π^0 Transition Form Factor

BESIII Monte Carlo, $\Psi(3770)$

$L_{\text{int}} : 927 \text{ pb}^{-1}$, Tagged Lepton: e^-



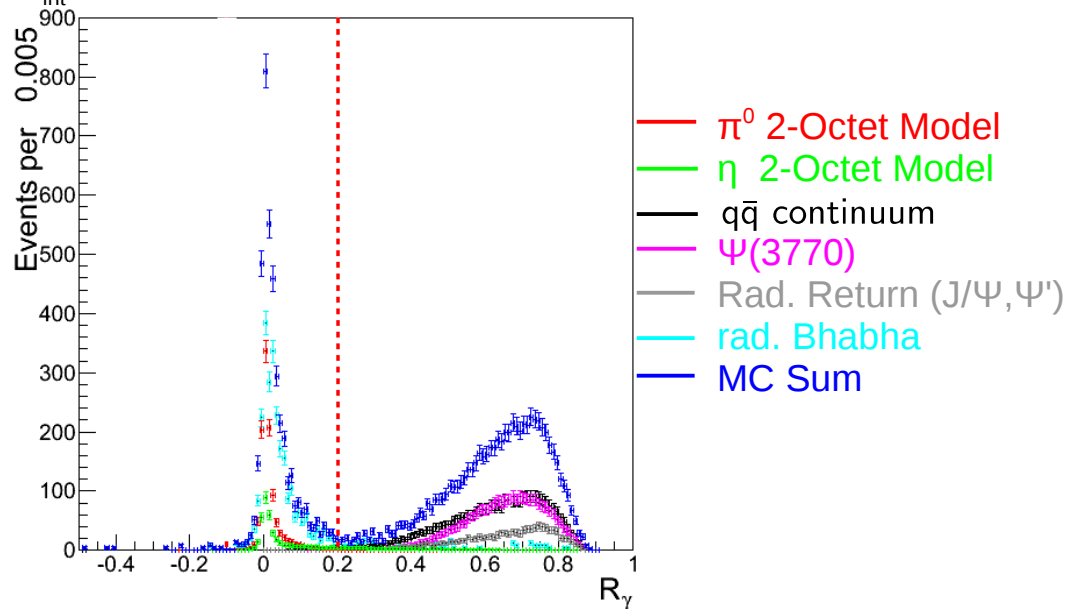
- Exactly one lepton
- Two to four photons
- $\cos\theta_{\text{untagged}} > 0.99$
- $\cos\theta_{\text{Helicity}} < 0.8$

- Angle between γ in π^0 rest frame and π^0 in lab
- Flat for signal
- Peaked for background
- Reject events with $\cos(\theta_H) > 0.8$

Space-like π^0 Transition Form Factor

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- Exactly one lepton
- Two to four photons
- $\cos\theta_{\text{untagged}} > 0.99$
- $\cos\theta_{\text{Helicity}} < 0.8$
- Reject hadronic background

- ISR results in wrong Q^2

- Useful observable:
$$r_\gamma = \frac{\sqrt{s} - E_{e^\pm \pi^0 \eta}^{CMS} - p_{e^\pm \pi^0 \eta}^{CMS}}{\sqrt{s}}$$

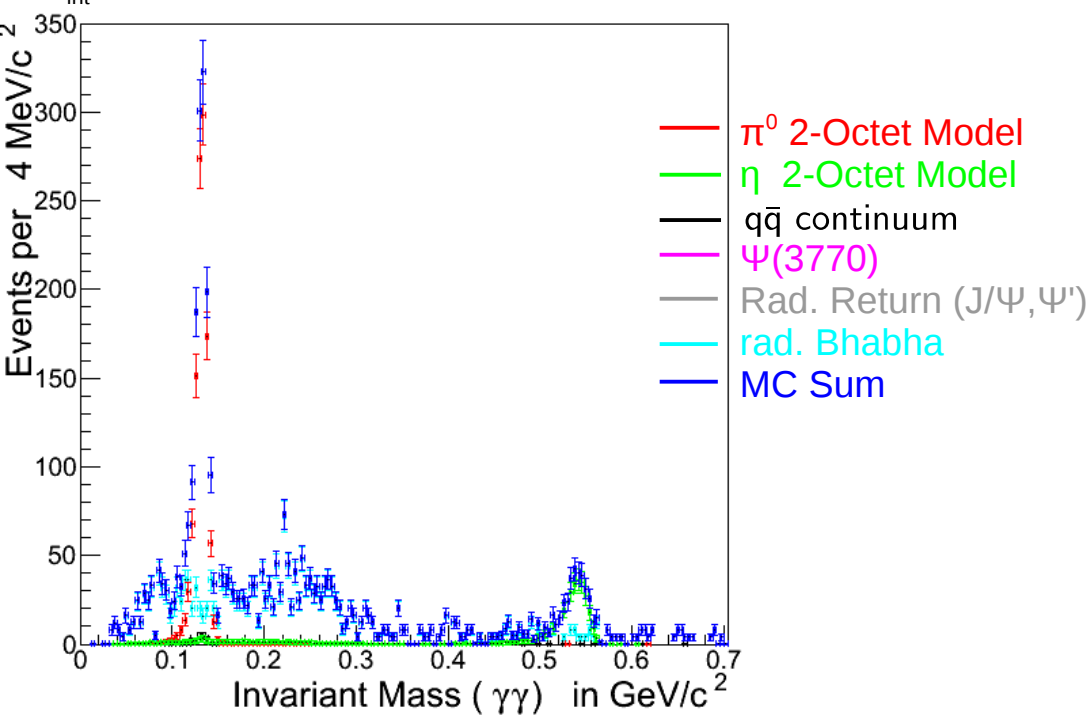
- If ISR,
$$r_\gamma = \frac{2E_\gamma}{\sqrt{s}}$$

- Reject events with $r_\gamma > 0.04$

Space-like π^0 Transition Form Factor

BESIII Monte Carlo, $\Psi(3770)$

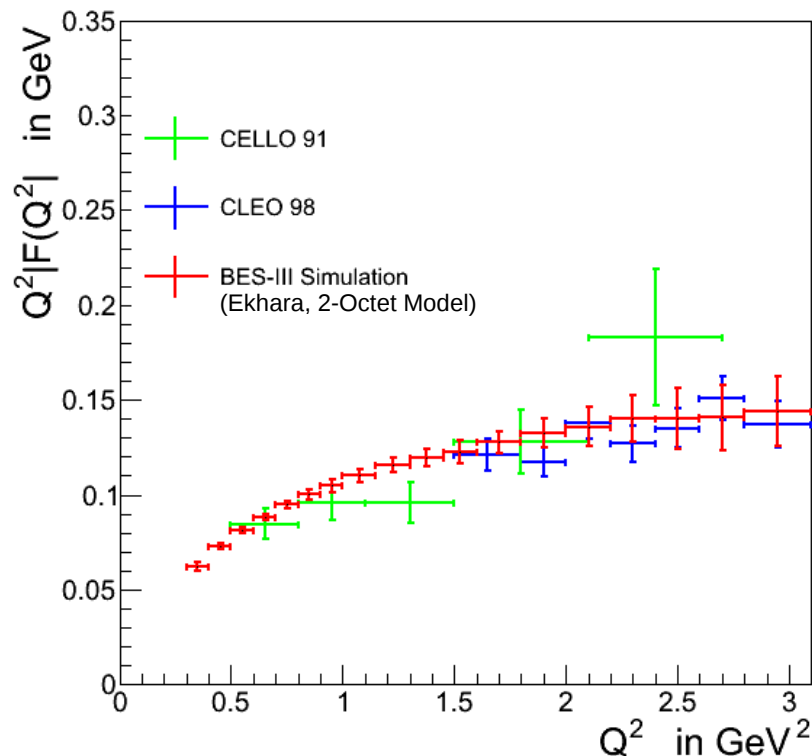
$L_{\text{int}}: 927 \text{ pb}^{-1}$, Tagged Lepton: e^-



- Exactly one lepton
- Two to four photons
- $\cos\theta_{\text{untagged}} > 0.99$
- $\cos\theta_{\text{Helicity}} < 0.8$
- Reject hadronic background

- Analysis useful for π^0 and η

Space-like π^0 Transition Form Factor



- Exactly one lepton
- Two to four photons
- $\cos\theta_{\text{untagged}} > 0.99$
- $\cos\theta_{\text{Helicity}} < 0.8$
- Reject hadronic background
- Bkg subtr. by counting π^0 yield per Q^2 bin
- $|F(Q^2)|^2$ extracted by division by WZW-MC
- Full BESIII $\Psi(3770)$ data set analyzed
- Competitive accuracy up to 3.1 GeV²
- Unprecedented accuracy below $Q^2 = 1.5$ GeV²

- Only statistical errors shown
- Systematic studies to be finalized
 - Main contribution: background subtraction

Contribution to a_μ

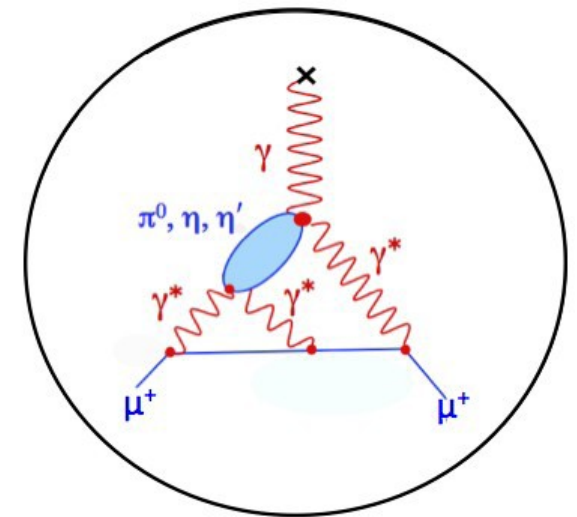
- Current accuracy of a_μ : $\sim 6.3 \times 10^{-10}$
- Contribution of π^0 : $\sim 7 \times 10^{-10}$ Knecht, Nyffeler
Phys.Rev.D65 (2002) 073034
- Expected accuracy of new experiments at FNAL and J-PARC: $\sim 1.6 \times 10^{-10}$

- Contributions of η and η' relevant!

$$\eta \sim 1.5 \times 10^{-10}$$

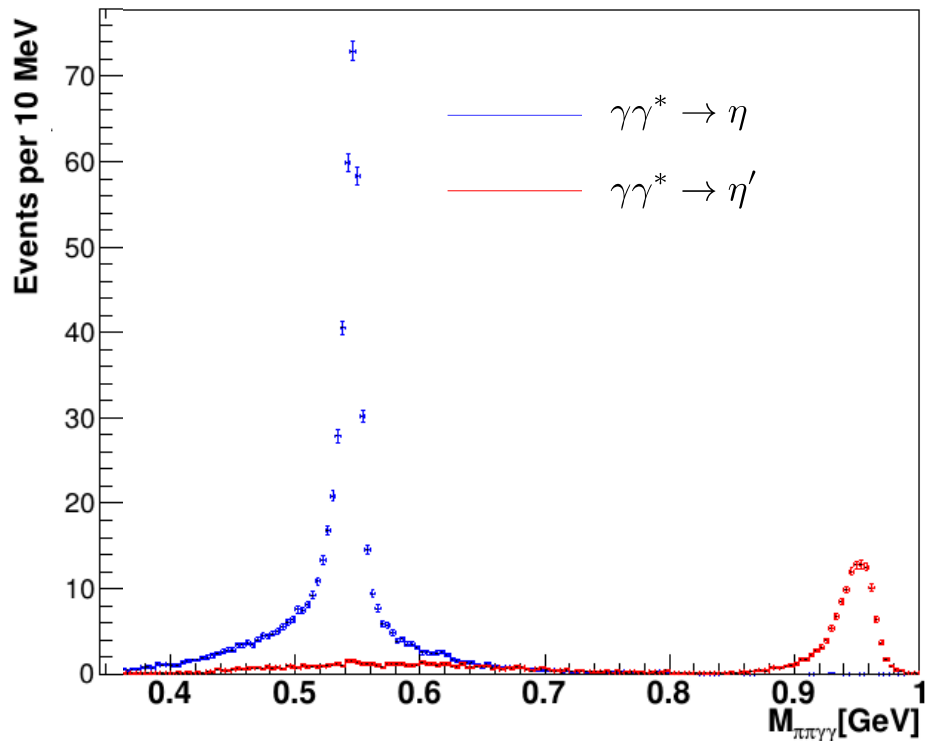
$$\eta' \sim 1.5 \times 10^{-10}$$

Knecht, Nyffeler
Phys.Rev.D65 (2002) 073034



Space-like η, η' Transition Form Factor

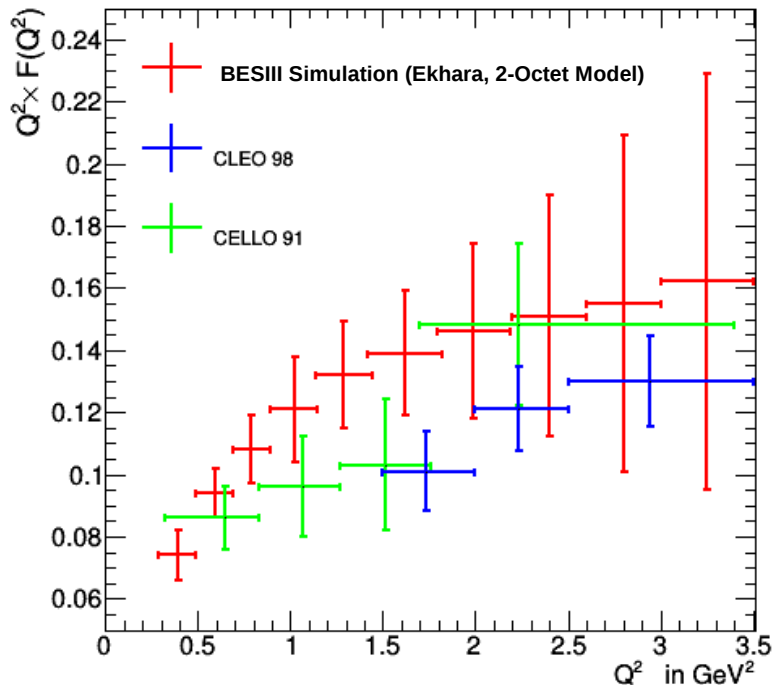
BESIII Simulation: $2.9 fb^{-1}$ @ 3.773 GeV



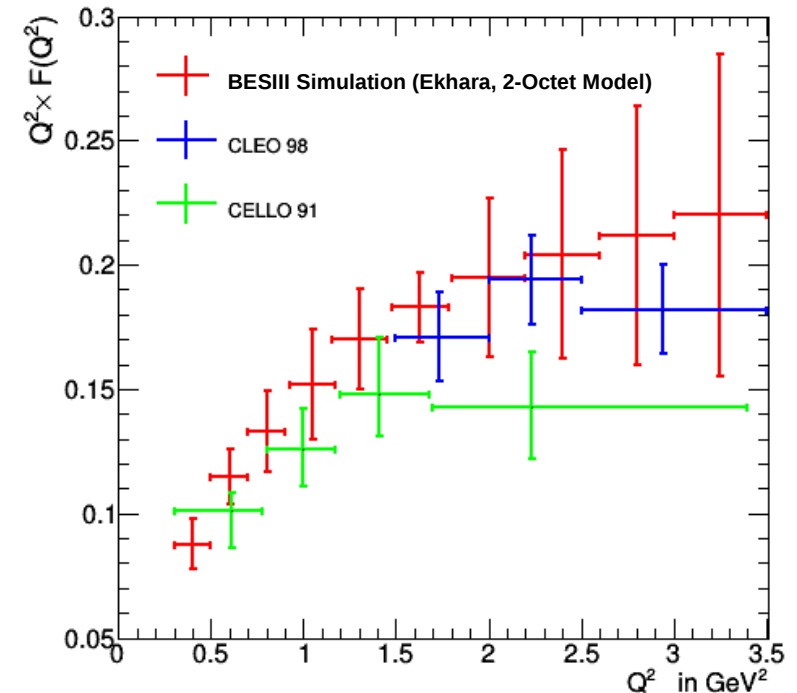
- $\eta \rightarrow \pi^+ \pi^- \pi^0$
- $\eta' \rightarrow \pi^+ \pi^- \eta$
- Any combination of
 - one positron
 - two charged pions
 - two photons
- $\cos\theta_{\text{untagged}} > 0.99$
- reject hadronic background
- Mass window cuts on $\gamma\gamma$ invariant mass
- Kinematic fit
- Relatively low background conditions

Space-like η, η' Transition Form Factor

$$F_{\eta, \gamma, \gamma^*}(Q^2)$$



$$F_{\eta', \gamma, \gamma^*}(Q^2)$$

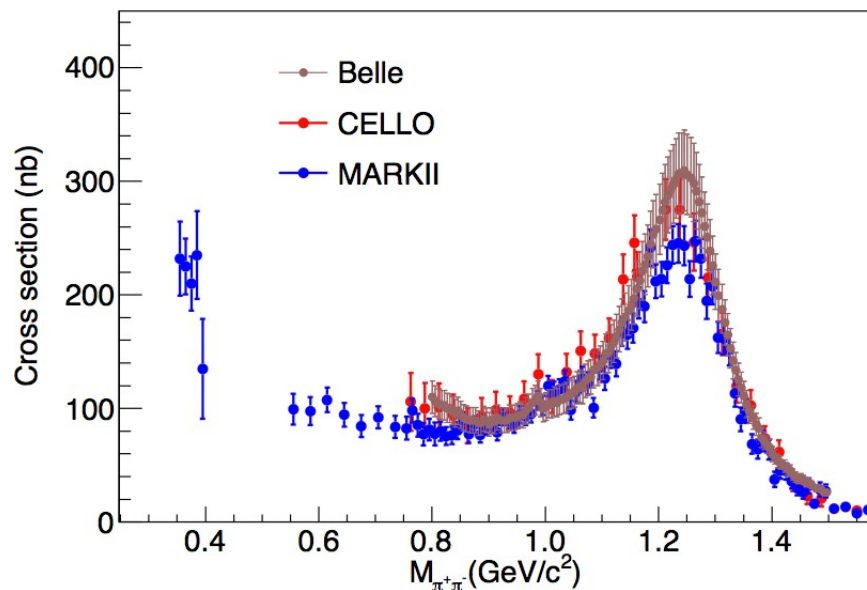


- Full BESIII $\Psi(3770)$ data set analyzed
- statistics compatible to previous measurements
 - only one decay channel of η and η' analyzed at BESIII
 - more data available
- Systematic studies to be done

Space-like $\pi^+\pi^-$ Transition Form Factor

- Additional Motivations:
 - Resonance parameters
 - Pion polarizabilities, pion structure
 - Essential for dispersive frameworks
 - Rescattering effects in low mass region
- Only untagged measurements so far

Collangelo, Hoferichter, Procura, Stoffer
JHEP 1409,091



MarkII, Phys. Rev. D42 (1990) 5

CELLO, Z. Phys. C56 (1992) 381

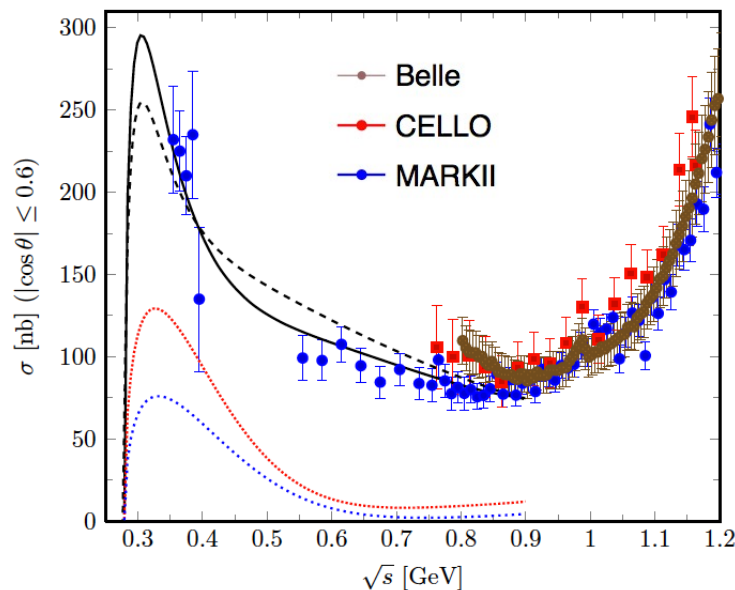
Belle, Phys. Rev D75 (2007) 051101

Space-like $\pi^+\pi^-$ Transition Form Factor

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Collangelo, Hoferichter, Procura, Stoffer
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Calculations by
Assmussen, Masjuan, and Vanderhaegen:

Untagged

Single-Tag ($Q_1^2 = 0.5 \text{ GeV}^2$)

Double-Tag ($Q_1^2 = Q_2^2 = 0.5 \text{ GeV}^2$)

Space-like $\pi^+\pi^-$ Transition Form Factor

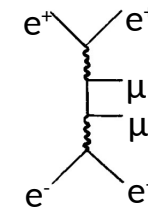
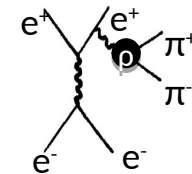
- At BESIII: Single-Tag measurement

- Using 1 fb^{-1} , collected at $\sqrt{s} = 4360 \text{ MeV}$
- Event selection analogous to single pseudoscalar analysis

- Major Backgrounds:

- $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$

- Radiative Bhabha scattering coupling to ρ (s + t channel)
 - MC generators missing



- $\gamma\gamma^{(*)} \rightarrow \mu^+\mu^-$

- Two-photon production of muon pairs
 - Precise MC generators available from LEP era (BdkRC + Diag36ABC)
 - Train ANN to suppress muon background

Space-like $\pi^+\pi^-$ Transition Form Factor



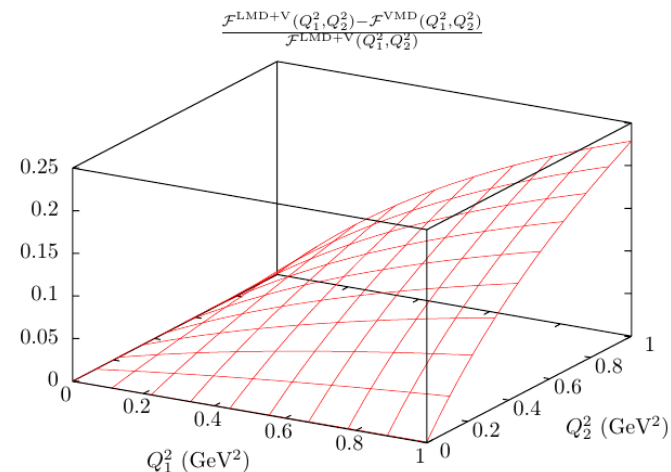
- Subtract remaining muon background from MC
- Subtract ρ contribution
 - Fit with Kühn-Santamaria parameterization
- Study pion mass in bins of Q^2 and $\cos\theta^*$
- Expectations:
 - About 5000 signal events at $\sqrt{s} = 4360$ MeV
 - Access to:
 - low momentum transfers $0.2 < Q^2$ [GeV²] < 2.0
 - low invariant masses $m_{\pi^+\pi^-} < M$ [GeV] < 2.0

Outlook: Double Tagged Measurements

- More than 7.7fb^{-1} on disk at $3.77 < \sqrt{s} [\text{GeV}] < 4.6$

- Double-tag measurements possible

- Measure $F(Q_1^2, Q_2^2)$
- 1st Step: Test TFF models
 - e.g. VMD vs. LMD+V



Calculations: A. Nyffeler

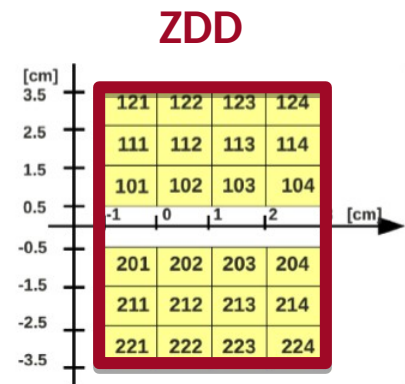
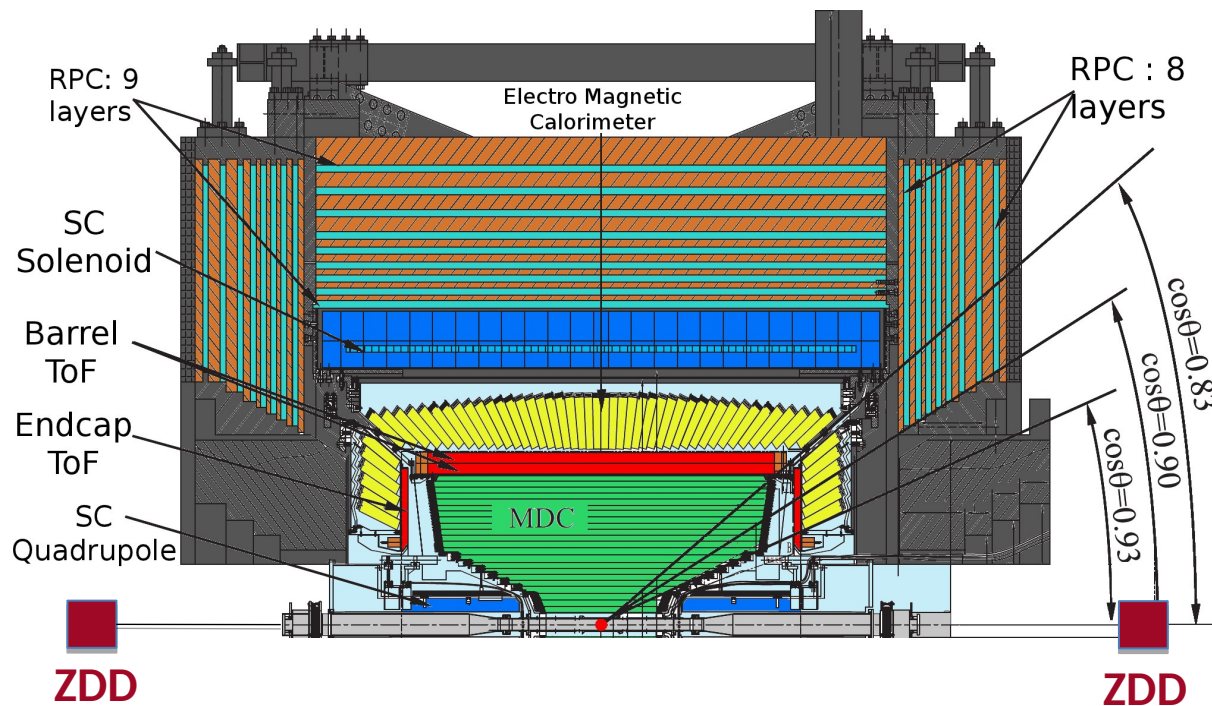
- Test polarization in $\gamma\gamma$ production
 - General two-photon cross section:

$$d\sigma = F \left\{ v_{TT} \sigma_{TT} + v'_{TT} \cos(2\tilde{\phi}) (\sigma_{\parallel} - \sigma_{\perp}) + h_1 h_2 v''_{TT} \frac{1}{2} (\sigma_0 - \sigma_2) \right. \\ \left. + v_{LL} \sigma_{LL} + v_{TL} \sigma_{TL} + v_{LT} \sigma_{LT} + v'_{TL} \cos(\tilde{\phi}) \tau_{TL} + h_1 h_2 v''_{TL} \cos(\tilde{\phi}) \tau_{TL}^a \right\}.$$

- $\tilde{\phi}$: azimuthal angle between lepton planes in $\gamma^* \gamma^*$ CMS
 - Allows to disentangle form factor contributions of multi-meson and tensor states
 - Requires precise measurement of angles

Outlook: Zero Degree Detector

- Tagging of photons and electrons at small angles
 - Polar angle range: 1 – 10 mrad
- Current design: Pb-SciFi, one sided
- Upgrade: Arrays of 48 PbWO crystals on both sides



Summary

- Two-photon physics program established at BESIII
 - Single-tag measurements of π^0 , η , and η' transition form factors
 - Unprecedented accuracy for $Q^2 < 1.5 \text{ GeV}^2$
 - Single-tag measurement of $\pi^+\pi^-$
 - First measurement at low Q^2 , low mass
 - To be extended to neutral final states
 - First double-tagged measurements $\gamma^*\gamma^* \rightarrow \pi^0$ started
- New prospects from tagging detectors